FLOW MEASUREMENT TRANSDUCERS AT LRC

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SUMMARY

A brief review is made of the flow rate measurement transducers in current use at the Langley Research Center. These include electronic in-line turbine and thermal transducers that directly sense volumetric and mass flow, and differential pressure transducers which are used to infer the flow rate through head-type flowmeters (orifice, nozzle and laminar). Experience shows that the turbine flowmeter, because of its accuracy, rangeability, and ease of application, is best suited to measure nearly all the liquid flow rates. Gas flow rates, depending on test requirements, are measured with a variety of flowmeters, including the turbine type.

INTRODUCTION

The importance of accurate flow rate measurements has grown steadily at this Center in recent years. This importance is linked directly to the development of space-oriented tools like the arc-heated tunnels for probing reentry phenomena, plasma accelerators for studying new methods of space propulsion, and regenerative life support test beds for developing life-sustaining systems for long-mission space craft. Furthermore, flow rate information is essential to experiments involving jet engine performance, gas concentration determinations, thrust and lift augmentation and gas mixing for ablative materials and hypersonic combustor studies. In meeting the flow measurement needs of these diverse research projects, the Instrument Research Division (IRD) has investigated the suitability of a variety of flowmeters and has adopted some for general use. Others are still under test in a continuing program to upgrade the Center's flow measurement capability. A summary of the scope and diversity of LRC's flow measurement activity is presented along with a brief discussion of some current flow transducers and examples of their application.

DISCUSSION

The summary is developed around a list (fig. 1) of the essential factors underlying the selection of a flowmeter for any project application, namely:

1. Fluid to be metered; this includes considerations of viscosity, density, homogeneity, and corrosiveness.

2. Flow range; this implies meter size, meter rangeability, and meter units required.

3. Flowing conditions; these include the operating static pressure, fluid temperature, and acceptable pressure drop.

4. Accuracy expected; this is influenced by factors of calibration, installation, environment, secondary measurements, signal conditioning, and recording media.

Fluids

Wide-spread requirements for measuring a variety of liquids and gases exist. Water at ambient temperature is the fluid in 90 percent of the liquid measurements. Other liquids are JP-4, propane, aqueous propylene glycol, Dow Corning DC 331, 90 percent concentration hydrogen-peroxide, hydrazine, and nitrogen-tetroxide. These fluids vary considerably in viscosity, corrosiveness, lubricity and toxicity. Gas flow measurements (other than air which is the fluid in most cases) often involve the inert fluids, helium, nitrogen, and argon. Other gases are hydrogen, oxygen and the hydro-carbons methane and ethane. Probably the most exotic of metered fluids have been molten lithium and a hydrazine-aluminum powder slurry. The lithium was used (after vaporizing) in a plasma accelerator and a description of the flow measuring system appears later in this discussion; the slurry (30 percent aluminum by volume) was tested as a rocket propellant by the Applied Materials and Physics Division and was measured with a 30-gpm magnetic flowmeter.

Flow Range

Liquid flow rate measurements range from about 5.3×10^{-5} gpm (0.2 cc/min) to 500 gpm. Covering the low range is a resistance type thermal mass flowmeter that measures the rate of water consumption of a water electrolysis unit in a regenerative life support system. Turbine flowmeters ranging in diameter from 3/16" to 2-1/2" handle most liquid flows from about 0.01 to 500 gpm.

Gas flows range from about 3.5×10^{-6} scfm (0.1 cc/min.) encountered in leak rate determinations to 12,000 scfm (15 lbs/sec.) air required to generate thrusts for the 16-foot transonic tunnel testing of jet powered models. The lower ranges are usually associated with gas mixing and combustion experiments, space equipment leak rates, and life support systems. Gas flows are measured with thermal, head-type, and turbine flowmeters.

Flowing Conditions

Flowing pressure and temperature conditions are as diverse as the Center's research projects. Some fluid temperature extremes have been -150°F of liquid nitrogen boil off flows and 600°F of the molten lithium mentioned previously. Most flows, however, are measured at ambient temperatures. Pressure conditions vary more than those of fluid temperature. Some notably uncommon pressures are 1000 psi required to force CO_2 flows to the high enthalpy arc of the Applied Materials and Physics Division, 15,000 psi behind the nitrogen gas flows of the Mach 19 hypersonic nitrogen tunnel, and 1.0-to-10 torr absolute pressures for air flows of experimental planetary enthalpy probes. Some facility water and hydrogen-peroxide pressures reach 1000 psi.

Accuracy

Generally the accuracy requirements vary with the experiment. Liquid measurements in the field can be made to 1.0 percent of reading with careful installation and recording techniques. With gas measurements, the uncertainty is about 1.0 percent of full scale. Here the accuracy has strong dependence upon the pressure and temperature measurements required for fluid density determinations, with pressure exerting the greater influence. Pressure transducers yielding 0.5 percent measurements are generally used, and open-bead thermocouple probes with $\pm 1^{\circ}$ tolerances are used to measure fluid temperature.

The most demanding accuracy requirements at LRC are of H_2O_2 and air measurements to thrust simulators used in correlating jet and nozzle performances. More is said of this later.

Liquid flowmeters are calibrated with a Brooks Instrument Co. dynamic time-weight standard certified by NBS to have an uncertainty of 0.15 percent (fig. 2).

Gas flowmeters are calibrated with a Cox Instruments, Inc. sub-sonic nozzle stand with an uncertainty believed to be less than 0.75 percent. Low-flow units (less than 1.0 scfm) are calibrated with a Brooks (George K. Porter) time-volume stand with an uncertainty of ± 0.5 percent.

TURBINE FLOWMETER

Because of its accuracy, ease of application and recordability, the turbine flowmeter is the most widely used flow instrument at LRC. Over 400 units exist, all of stainless steel, with measuring capabilities of 0.0125 gpm to 500 gpm for liquid and 0.1 to 250 acfm for gases. Most standard turbines have rotors suspended on ball bearings and operate at pressures to 3000 psi.

The turbine's working principle is simple yet precise (fig. 3). The fluid drives a freely turning rotor (C) suspended in a flow passage (A) of constant area. The rotor (B) turns at a speed proportional to volumetric flow rate. As each helical rotor blade interrupts the magnetic field of a closely coupled pickup coil (D), one cycle of alternating voltage (typically sinusoidal) appears at the coil terminals. The frequency of the generated voltage is a measure of the flow rate while the sum number of cycles is a measure of total flow. A convenient, universally used calibration factor for this system is K = cycles/gallon (for liquids) or cycles/cubic ft (for gas). The linear operating range (constant K) depends on design, size, and fluid viscosity. A 10-1 linear range is common with transducers having full-scale capacities of over 1 gpm for liquid, and 1 acfm for gas. In smaller transducers, small bore, low flow, and fluid viscosity combine to generate non-linear calibrations. Repeatability, however, for all properly functioning turbines is better than 0.25 percent. For gas measurements, recorded values of fluid temperature and pressure are required to determine fluid density which is multiplied by the volumetric flow rate (given by the turbine's output frequency) to compute mass flow rate.

Most LRC turbines have full scale output frequencies of 1200 Hz at output voltages ranging to 1000 millivolts peak-to-peak. These outputs are fed to frequency-to-analog convertors which respond only to variations in frequency and are insensitive to waveshape or changing amplitude. The convertors emit useful low impedance millivolt signals suitable for recording and square-wave signals, which are synchronous with input frequencies, for driving counters. The standard conversion uncertainty is ±0.1 percent of full scale at steady-state flow conditions.

Liquid Applications

A typical facility requirement is recording the history of water coolant flow rates to the electrodes and other elements of any arc heater which is used for studying low density, high temperature, reentry phenomena. Mass flow data are required to assure adequate cooling, perform heat balance calculations and determine test gas enthalpy. Fig. 4 shows a group of 2-inch, 250 gpm turbines in the 20-megawatt arc heated facility of the Aero-Physics Division. They measure 800 psi water flows to the arc electrodes, nozzle, and test section wall. The convertors for these flowmeters (and others) are shown in the control room view of fig. 5. Some have capability for driving meter relays designed to operate emergency shut-down equipment in the event of inadequate cooling.

Another application of the turbine flowmeter is shown in fig. 6. This system was used in the RAM C flight test conducted by the Flight Instrumentation Division for studying radio blackout during reentry. A simple sketch of the vehicle is also shown. A 1/2-inch turbine flow transducer measured the flow rate of water that was injected into the flow field near the nose of the vehicle in an effort to reduce the detrimental plasma effect on radio communications. The water droplets served as recombination centers for positive ions and electrons resulting in signal strength enhancement up to about 30 db. The program called for injection of rapid spurts of water (up to 0.66 lb/sec.) at vehicle speeds of 27,000 ft/sec. and at heights of 300,000 ft. To meet the flow system response requirement of 5 milliseconds, the usual frequency convertor was omitted and the turbine's output, after clipping, was fed directly to a 40 kilocycle voltage controlled oscillator (VCO) for telemetering to ground receivers. The flow rate was obtained from oscillographic readings of the frequency.

Gas Application

An example of gas turbine flowmetering is shown in figs. 7 and 8. Fig. 7 shows a 3-inch diameter, 12-bladed turbine flow transducer which measures up to 15 lb/sec. of air to jet simulators. Fig. 8 is a schematic diagram of the complete flow metering run including the turbine flow transducer. The jet simulators are used for correlating aerodynamic data obtained from jet-powered models in the 16-foot transonic and 4-foot supersonic wind tunnels. Thrusts up to 1000 lbs are generated by exhausting the compressed air through the test jet nozzles. Accurate flow measurements are required since jet thrust coefficients are determined directly from mass flow measurement values. The system accuracy approaches 1.0 percent of flow rate over much of the 10-1 metering range.

The air is regulated down from 1800 psi and heated to 90°F to prevent jet nozzle geometry changes from frost accumulation. Flowmeter static pressure is maintained at 800 psig and measured with a 0.25 percent wsg transducer. The temperature is measured with an open-bead copper-constantan thermocouple probe. The pressure and temperature values are needed to determine fluid density. The mass flow rate is the product of density and volumetric flow rate.

Two-inch flowmeters were first applied in an attempt to restrict system size. However, these meters failed after 15 hours of operation because of accelerated bearing wear due to excessive metering velocities. The 3-inch meter now gives about 100 hours of trouble free operation before bearing replacement is necessary. This life extension resulted from (1). reduced velocities inherent in the larger diameter and (2), an improved bearing system where the 440C stainless steel balls are sealed with stainless steel shields and are silicone-lubricated. Four-inch diameter flowmeters lubricated with light oil have operated for 200 hours without performance loss.

These flowmeters were originally calibrated at the Colorado Engineering Experiment Station which is headed by Professor Tom Arnberg, and were checked at LRC on the Cox flow stand up to 2 lb/sec. On-site meter verification (after bearing change) is made with sonic flow nozzles also calibrated at the Colorado Engineering Experiment Station.

THERMAL MASS FLOWMETERS

Small gas flow rates (<1 scfm) are often measured with thermal mass flowmeters that employ heat transfer sensing mechanisms. Their output (both visual and electrical) are related directly to the convenient engineering mass flow units of lbs/sec., lbs/min., or scc./min., the latter being a volumetric term which defines the gas density at standard atmospheric conditions. Thermal mass flowmeters are useful for (1) monitoring and recording small gas flows into plasma accelerators, (2) determining leak rates of space chambers and inflatable satellites (3), studying the combustion reaction of gases, and (4) determining the relative porosity of acoustical and ablative materials. These flowmeters indicate the true mass flow rate without requiring correction for temperature and pressure variations over fairly wide ranges of these flow conditions.

Several manufacturers market various forms of thermal flowmeters using resistance bridge, thermocouple, thermistors, hot-wire elements for sensing mechanisms. All include some form of in-line transducer and a signal-conditioner meter unit. This discussion will cover two types (fig. 9) in use at Langley: The thermocouple type and the thermistor type, both of which emit output voltages which are a function essentially of mass flow and gas heat capacity.

Thermocouple Type

Simple sketches showing the thermocouple-type flow transducer's basic sensing mechanism appear at the top of fig. 9. At zero flow the differential thermo-electric output of the two thermocouples on the heated tube is also zero. When gas flows through the tube, the assymetrical cooling at the thermocouples produces a differential voltage that is directly proportional to mass flow rate. The approximately 100 units at Langley vary in flow range from 0-5 scc/min. to 0-20,000 scc/min. Some units of higher ranges using laminar by-pass elements also exist for flows to 5 scfm.

These flowmeters are accurate to about 2 percent of full scale and do not require pressure and temperature corrections between 0.1 to 250 psia and 40° to $140^{\circ}F$, respectively. With calibration over narrower pressure and temperature ranges, the accuracy is 1.0 percent of full scale at better than 1/2 percent repeatability. Other advantages are their minimal pressure drops (typically 1" - 2" H_2O for most units) and low-impedance linear output, (0-5 millivolt to 0-10 volt). These meters require reasonably delicate handling, periodic calibration and upstream filtering in order to maintain a desirable level of performance.

Lithium Flow System

Fig. 10 depicts the use of the thermocouple flowmeter in a system which was used to meter molten lithium to a Hall current plasma accelerator of the Aero-Physics Division. Most magneto-plasmadynamics experiments for deep space propulsion had been performed by ionizing and accelerating a variety of gases. Thought was later given to vaporizing and ionizing the alkalai metals because of their lower ionization potential.

Lower ionization potential reduced the energy requirements for the ionization process and made more energy available for accelerating the plasma. Lithium was chosen for the first experiments because its outer ring single electron could be readily dislodged. For optimum correlation with the gas tests, however, the lithium flow rates were fixed at the gas flow rates of .010

to .025 grams/sec. At molten lithium density of .544 grams/cc, the maximum volume flow rate was 2.75 cc/min., a minuscule rate which posed formidable measurement problems. The 600°F molten lithium temperature and the corrosiveness of the lithium compounded the measurement problems.

The chosen flow system, shown in simplified form, comprises a volume displacement technique where flow of an inert gas (helium because of its insolubility in lithium) displaces the lithium in the reservoir. Consequently, by the Law of Continuity, a measure of the helium volume flow rate is precisely that of the lithium forced from the reservoir. The helium pressure and temperature above the lithium were carefully monitored, with the pressure maintained at three atmospheres and the lithium temperature at 600°F. Preset flow rates were controlled with a modified Brown Electrik servoamplifier, motor and gear train which drove the high-resolution, copper-seated metering value. A 0-5 scc/min. thermocouple mass flowmeter was calibrated with helium under test flowing pressure and temperature conditions.

The flow curves show flowmeter readings plotted against lithium mass flow rate. The upper curve is the lithium flow rate inferred from the flowmeter readings and computed from the equations of continuity and state. The lower curve represents the actual flow determined by the timed collection of molten lithium. The flowmeter generally indicated 85 percent of the actual flow rate in repeated calibrations. The systematic error was mostly attributed to the helium calibration of the flowmeter. The time-volume standard used to perform the calibration employed a mercury-sealed piston driven by the helium gas and was designed to handle much larger flows than the 0-5 scc/min. Thus the standard would tend to minimize the effects of small leaks. However, the on-site flow metering system was found to be repeatable to about 2 percent and constituted a major improvement over previous nozzle methods used to measure flows of alkalai metals.

Thermistor Type

In the thermistor mass flow system (fig. 9) a self-heated bead thermistor loses heat to the fluid stream and the electrical power required to maintain the thermistor at a fixed resistance (temperature) is related to mass flow rate. A second thermistor compensates the sensor's non-linearity so that the 5 volt dc output is linear with mass flow rate. A panel meter provides instant readout of mass flow in percent of rated flow capacity. Units are available with capacities of 3.3×10^{-3} to 50 lb/min. Again, like the thermocouple types, these flowmeters impose negligible pressure drop and indicate true mass flow rates over fairly wide pressure and temperature ranges without correction when careful application techniques are practiced.

PRESSURE TRANSDUCERS FOR HEAD-TYPE FLOWMETERS

High Pressure Flows

At this center, wire strain gage and potentiometer type transducers (fig. 11) are generally used to measure the flow-proportional differential pressure (ΔP) across the restricting element in head-type compressed gas flow systems. All emit output signals that are compatible with LRC's data aquisition systems and perform with combined hysteresis and non-linearity errors of less than 0.75 percent of full scale. Typical ΔP ranges are from 0-10 to 0-250 paid in transducers operating at line pressures from 150 to 5000 psi.

Experience with head-type compressed gas flow measurement systems shows that the ΔP transducer must be able to sustain over-loads many times its design ΔP range because of high pressure transients that are often generated within these systems. Most of the center's ΔP transducers have adequate overload characteristics for nearly all of the high-pressure flow work at line pressures to 1500 psi. Some (the potentiometer type included) can sustain ΔP overloads to 6000 psi without degrading significantly their performance. Important design features of the most reliable transducers are (1) hydraulically damped force-summing devices, (2) effective mechanical stops, and (3) insensitivity to high common-mode pressures.

A major disadvantage of the potentiometric transducer, however, is the wire-wound potentiometer with its inherent resolution and mechanical problems. Currently, IRD's Force Measurement Section has adopted a Hall effects transducing system to this unit in place of the potentiometer. Results from early laboratory and field tests are highly encouraging.

Low Pressure Flows

For small gas flows both in the atmospheric and subatmospheric pressure flow regions, capacitance pressure transducing systems are often used. In the atmospheric case, laminar flow elements are used to reduce the Reynolds numbers to values less than 2000 so that the pressure drop becomes linear with volume flow rate. The capacitance pressure systems with a 1000-to-1 rangeability are well suited for laminar flow elements whose ability to measure near-zero flows is limited only by the pressure instrument. In the sub-atmospheric case, repeatable flow-proportional pressure data from sonic nozzles operating at 1 to 100 torr pressure have also been obtained with the capacitance gage. This system employs a transducer consisting of a high precision, stable capacitance voltage divider of which the variable element is a thin, prestressed metallic diaphragm. Positioned between fixed capacitance plates, the diaphragm, when acted upon by pressure inputs, amplitude-modulates the carrier voltage which is applied to the fixed plates. After demodulation, the output appears as a 0-5 volt dc signal which is linear with pressure to within ±0.5 percent of full scale for each of 7 selectable ranges, and repeatable to better than 0.25 percent. Typical transducer ranges are ±10, 50, 100, and 1000 torr.

CONCLUDING REMARKS

A brief discussion was presented on the nature of fluid flow measurement requirements at LRC and the transducers which are currently being applied to meet these requirements. The following statements reflect the present flow measurement activity:

(1) Turbine flow transducers are used to measure about 90 percent of the liquid flow rates; most are used for water coolant flows in arc-heated facilities.

(2) Gas flow rates are handled with a variety of instruments including thermal mass flow transducers, turbine flow transducers, and differential-pressure transducers in head-type flow systems.

(3) Measurement capabilities range from 5.3×10^{-5} gpm (0.2 cc/min) to 500 gpm for liquid and from 3.5×10^{-6} scfm (0.1 cc/min) to 12,000 scfm (15 lb/sec) for gases.

(4) Measurement uncertainties for liquids are generally 1.0 percent of flow rate; those for gases, 1.0 percent of full scale flow rate.

1. FLUIDS (VISCOSITY, DENSITY, HOMOGENEITY, CORROSIVENESS)

LIQUIDS		GASES	
WATER	PROPYLENE GLYCOL	AIR	CARBON DIOXIDE
JP-4	DOW CORNING 331	NITROGEN	METHANE
PROPANE	NITROGEN TETROXIDE	HELIUM	HYDROGEN
HYDROGEN PEROXIDE	HYDRAZINE	ARGON	ETHANE
MOLTEN LITHIUM	HYDRAZINE-ALUMINUM SLURRY	OXYGEN	HYDROGEN SULPHIDE

2. FLOW RANGE (METER SIZE, RANGEABILITY)

5.3×10^{-5} gpm (0.2 cc/min.) TO 500 gpm

3.5×10^{-6} scfm (0.1 cc/min.) TO 12,000 scfm

3. FLOWING CONDITIONS (PRESSURE, TEMPERATURE, PRESSURE DROP)

PRESSURE: TO 1000 PSI	.02 TO 15,000 PSIA
TEMPERATURE: MOSTLY AMBIENT	-150° TO 100° F

4. ACCURACY (CALIBRATION, INSTALLATION, SECONDARY MEASUREMENTS, SIGNAL CONDITIONING, RECORDING)

MEASUREMENT UNCERTAINTY:

1.0 PERCENT OF FLOW RATE

1.0 PERCENT OF FULL SCALE

CALIBRATION:

BROOKS 9910 DYNAMIC WEIGH STAND (300 gpm, $\pm$ 0.15 PERCENT UNCERTAINTY)

COX 610 AIR PRECISION NOZZLE STAND (2 LB/SEC., $\pm$ 0.75 PERCENT UNCERTAINTY)

FIG. 1 SUMMARY OF LRC FLOW MEASUREMENT ACTIVITY.

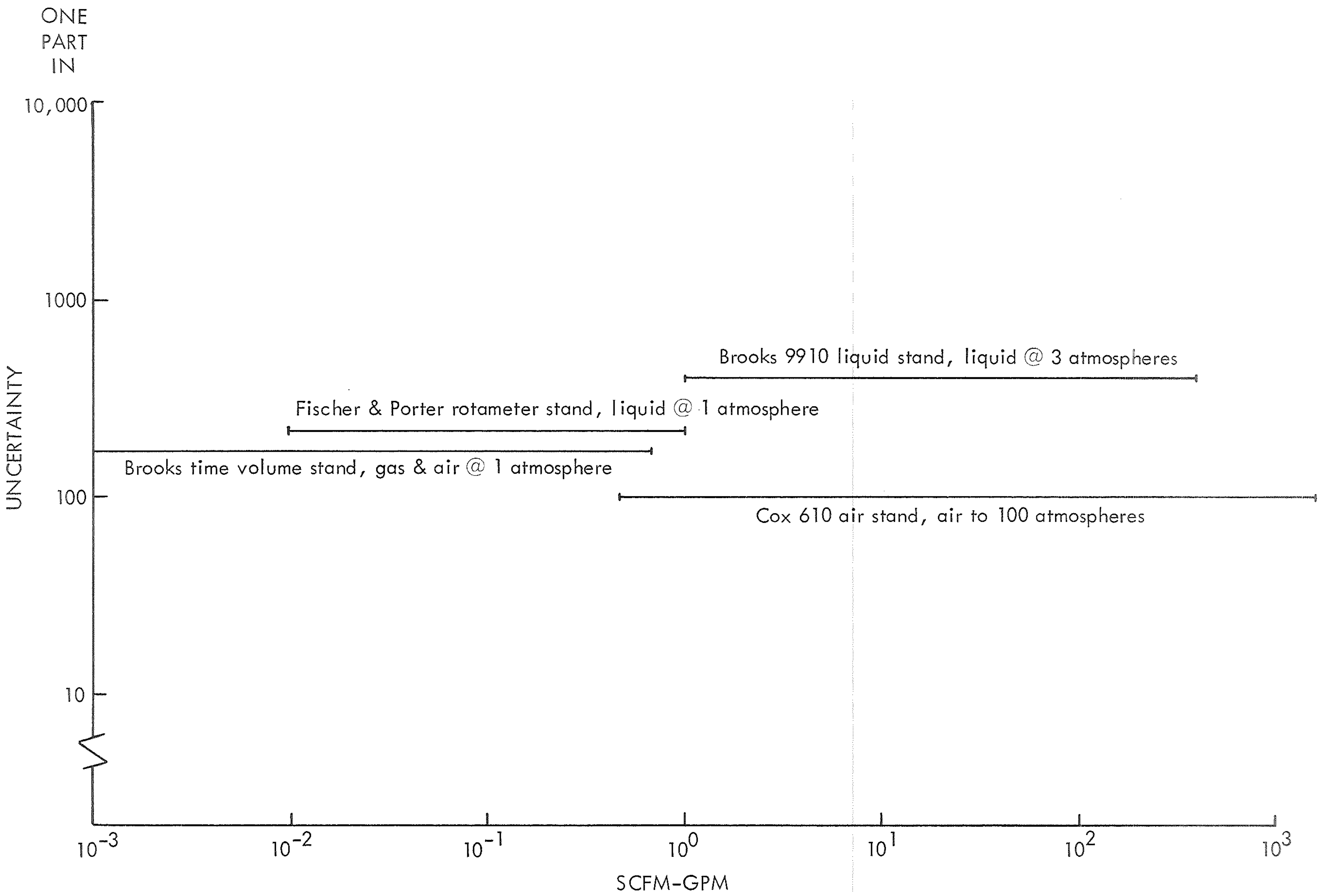

FIG. 2 SCOPE AND UNCERTAINTIES OF LRC FLOWMETER CALIBRATION EQUIPMENT

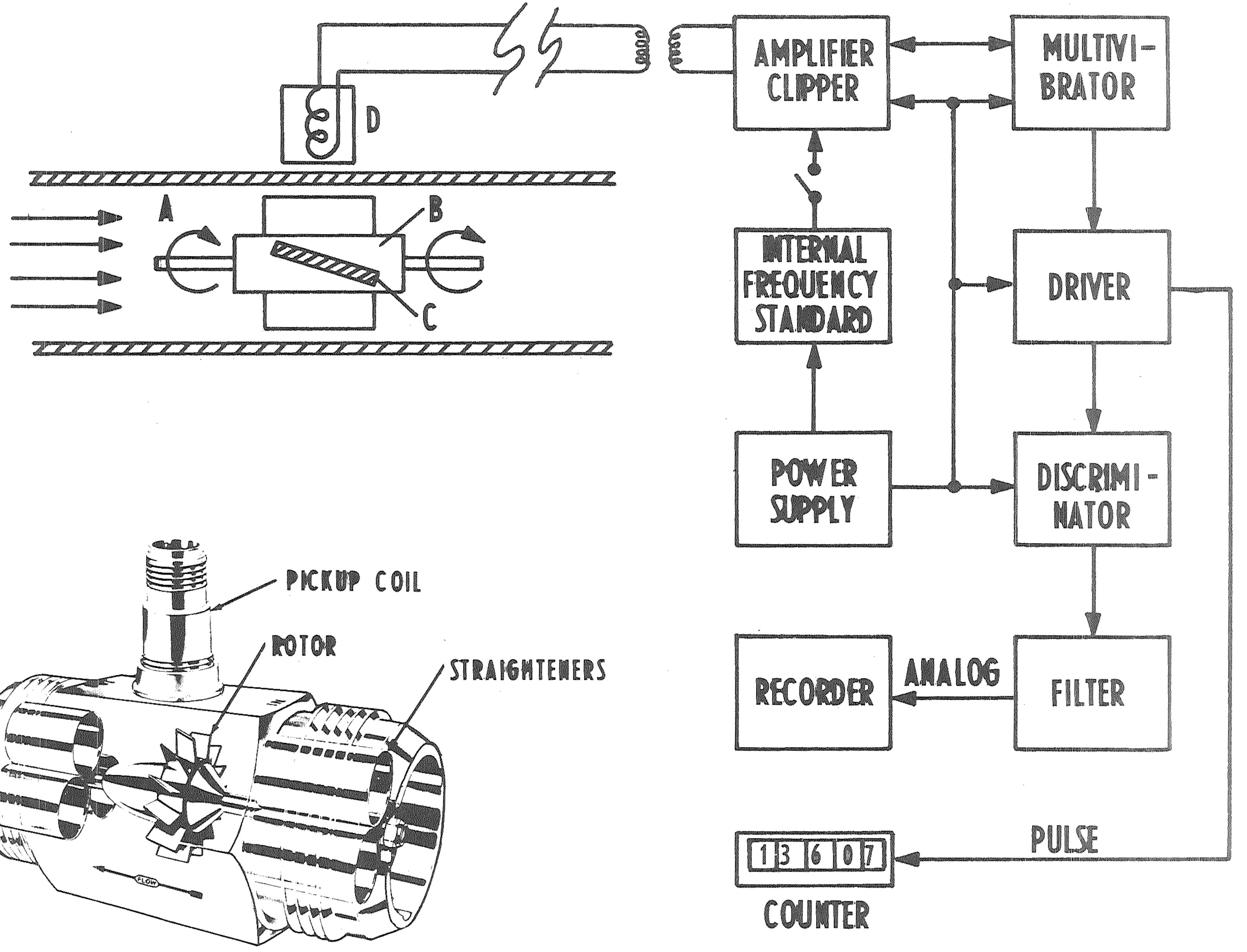

FIG. 3 TURBINE FLOWMETER SYSTEM.

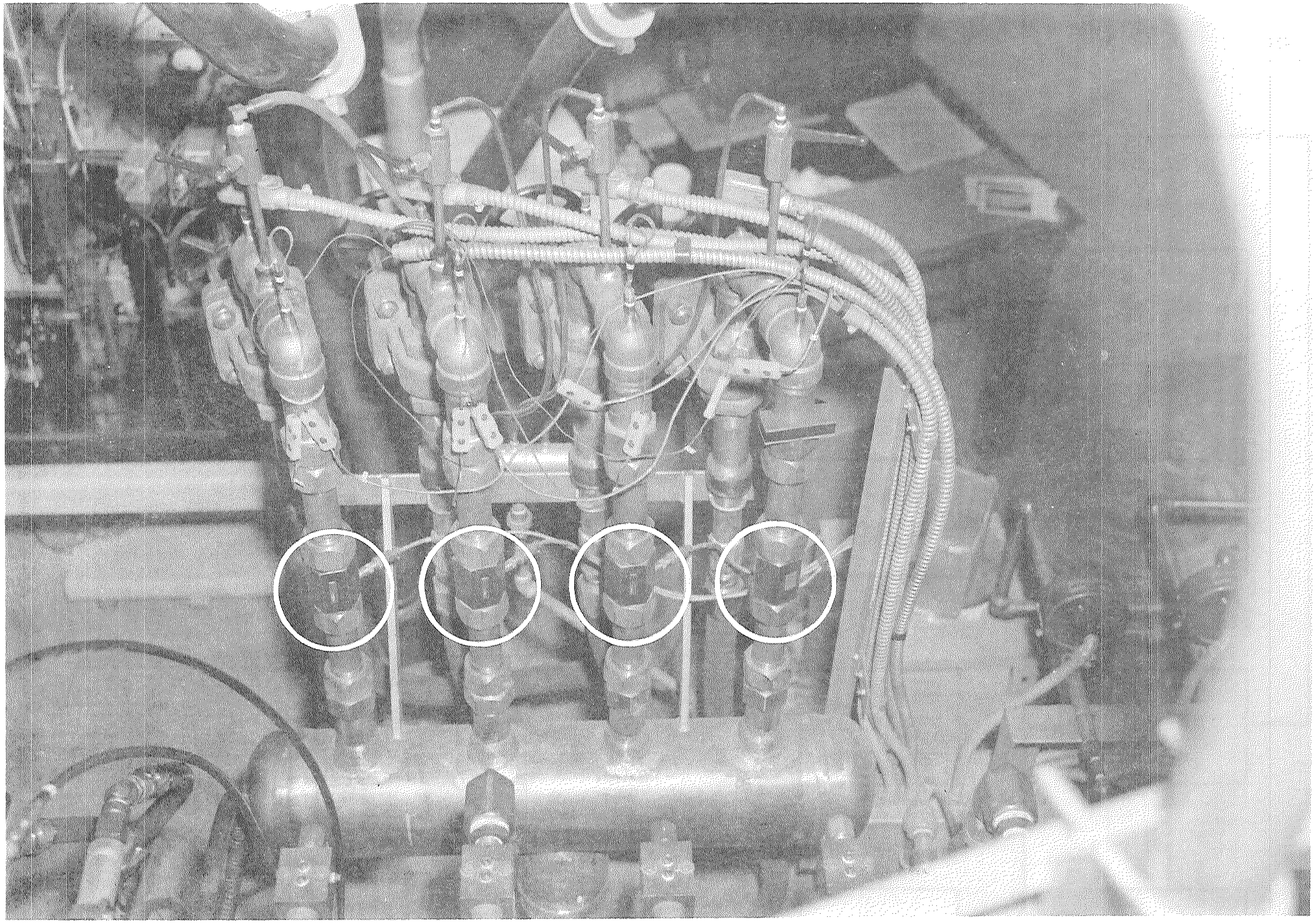

FIG. 4 TURBINE FLOW TRANSDUCERS MOUNTED IN THE WATER COOLANT SYSTEM OF AN ARC HEATER.

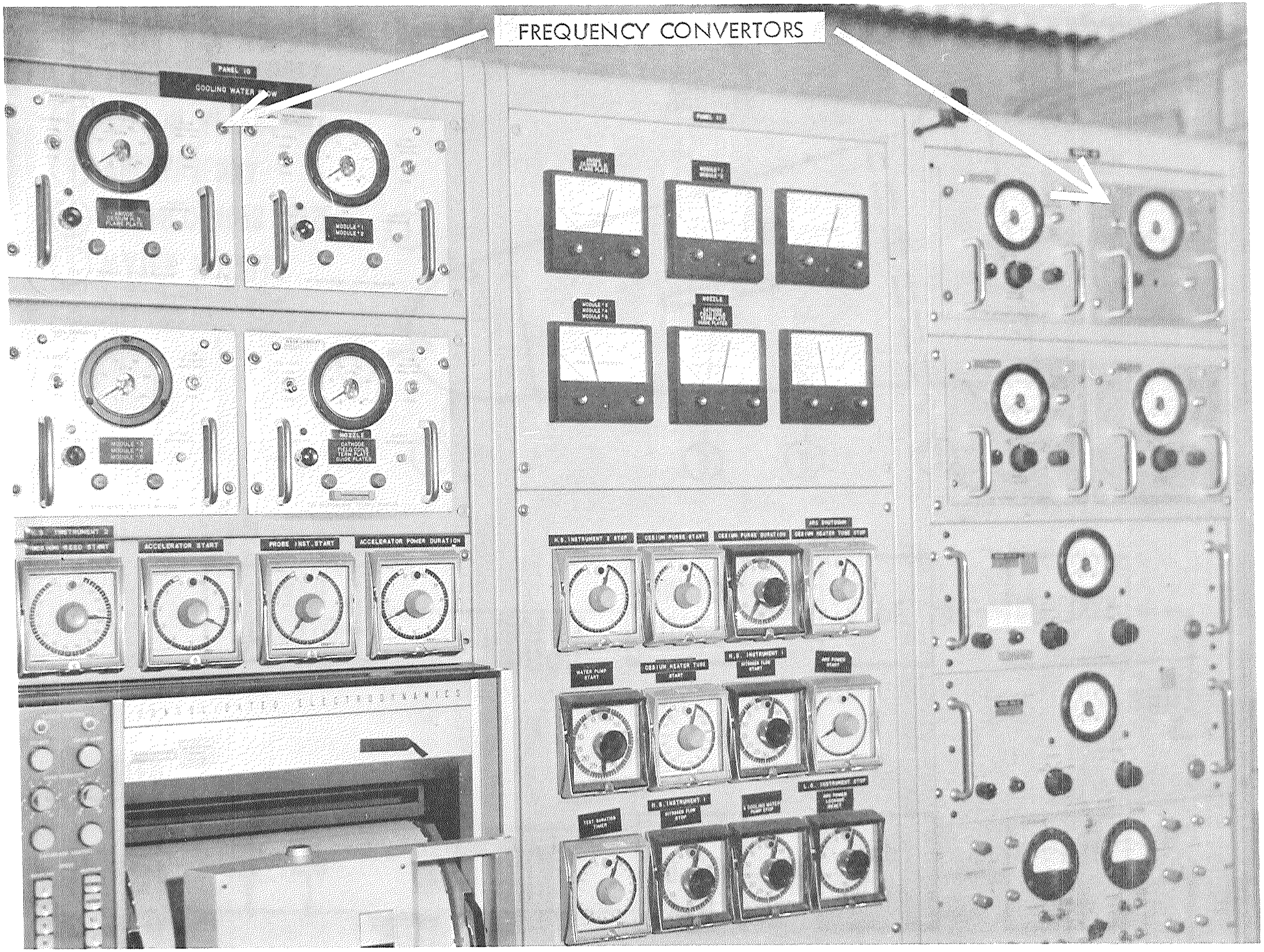

FIG. 5 CONTROL ROOM INSTALLATION OF FREQUENCY CONVERTORS

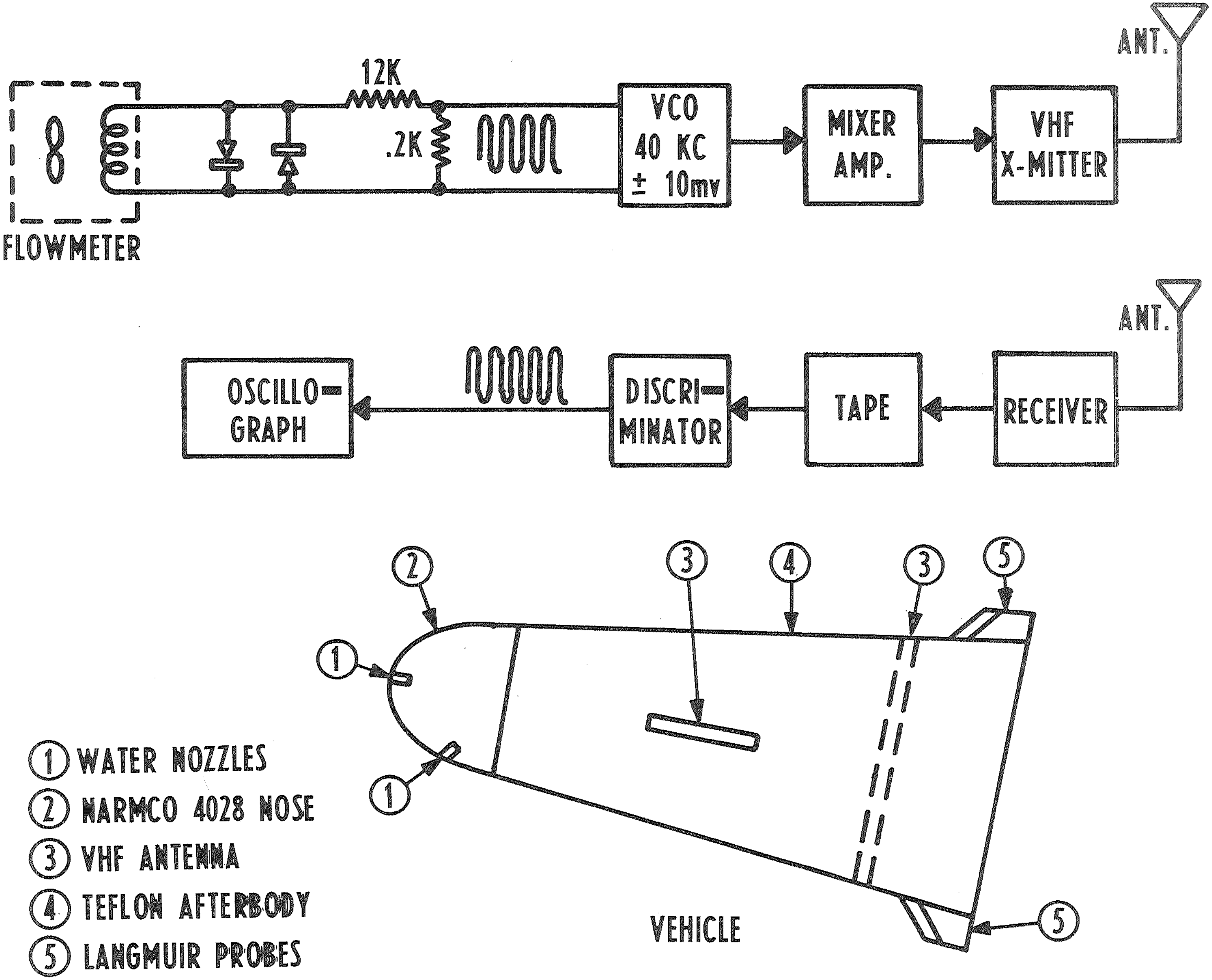

FIG. 6 RAM C WATER FLOW MEASUREMENT SYSTEM.

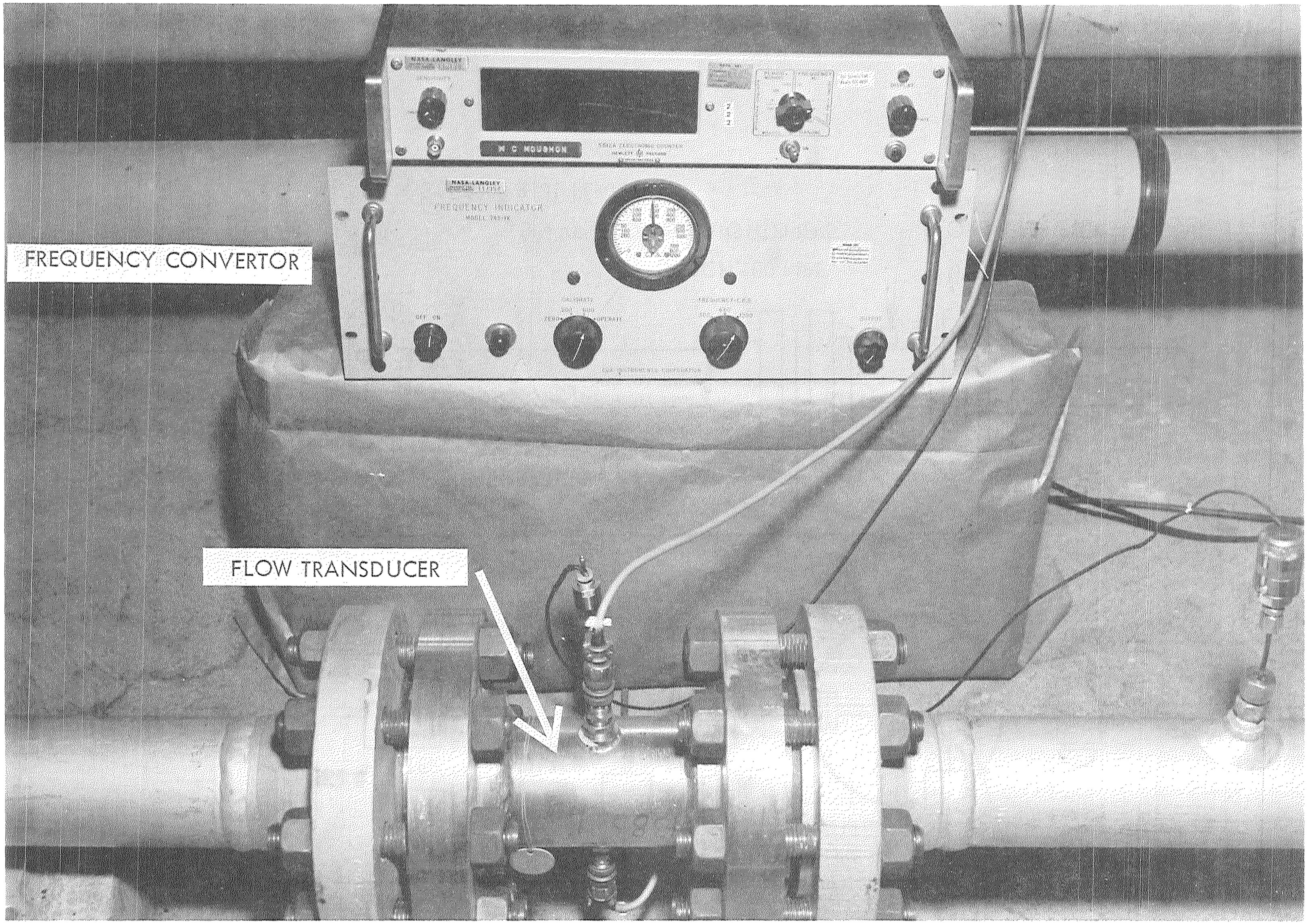

FIG. 7 3 - INCH, 15 LB./SEC. TURBINE FLOW SYSTEM FOR COMPRESSED AIR FLOWS.

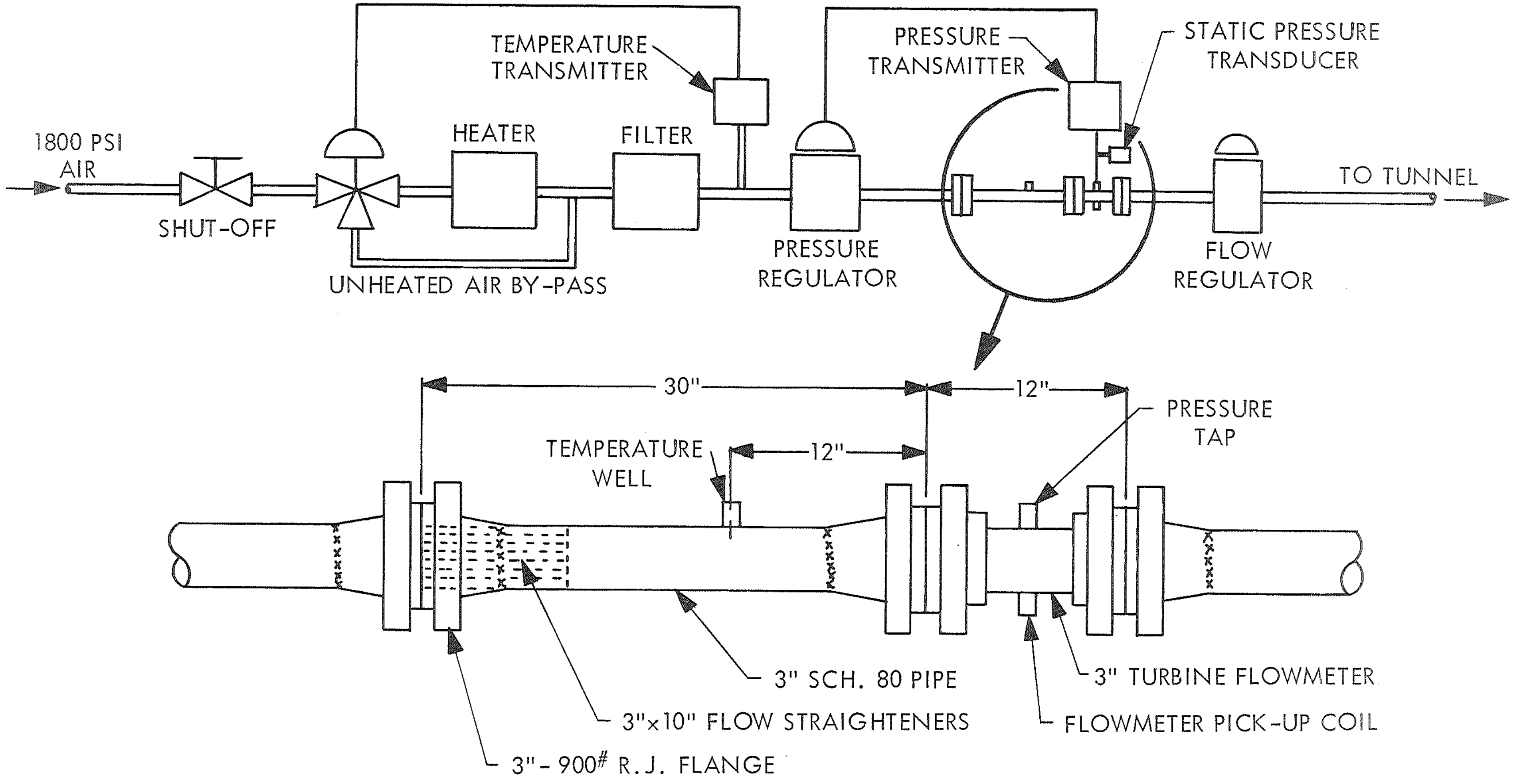

FIG. 8 - 16FT. TUNNEL HIGH PRESSURE AIR TURBINE FLOWMETER SYSTEM.

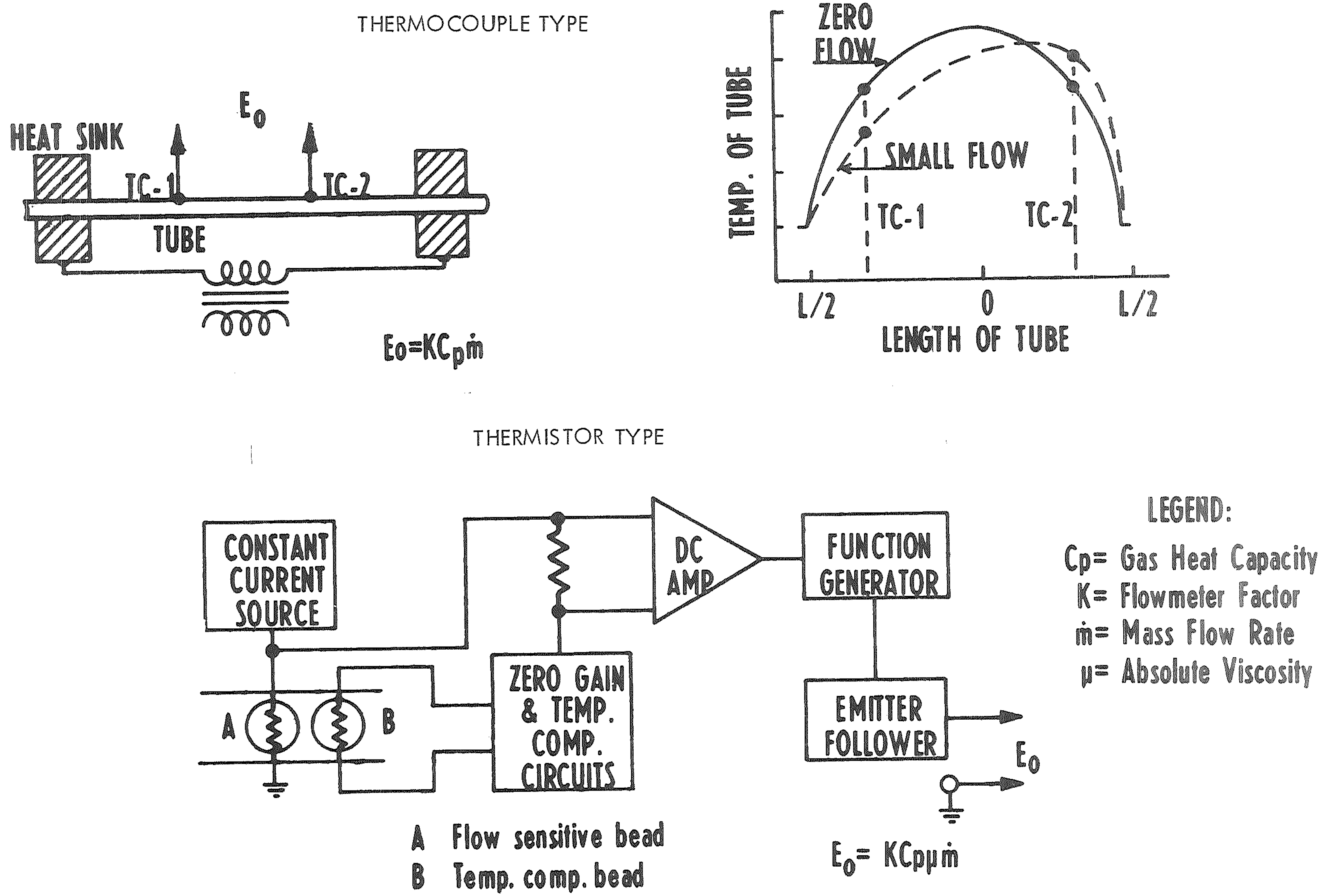

FIG. 9 THERMAL MASS FLOWMETERS.

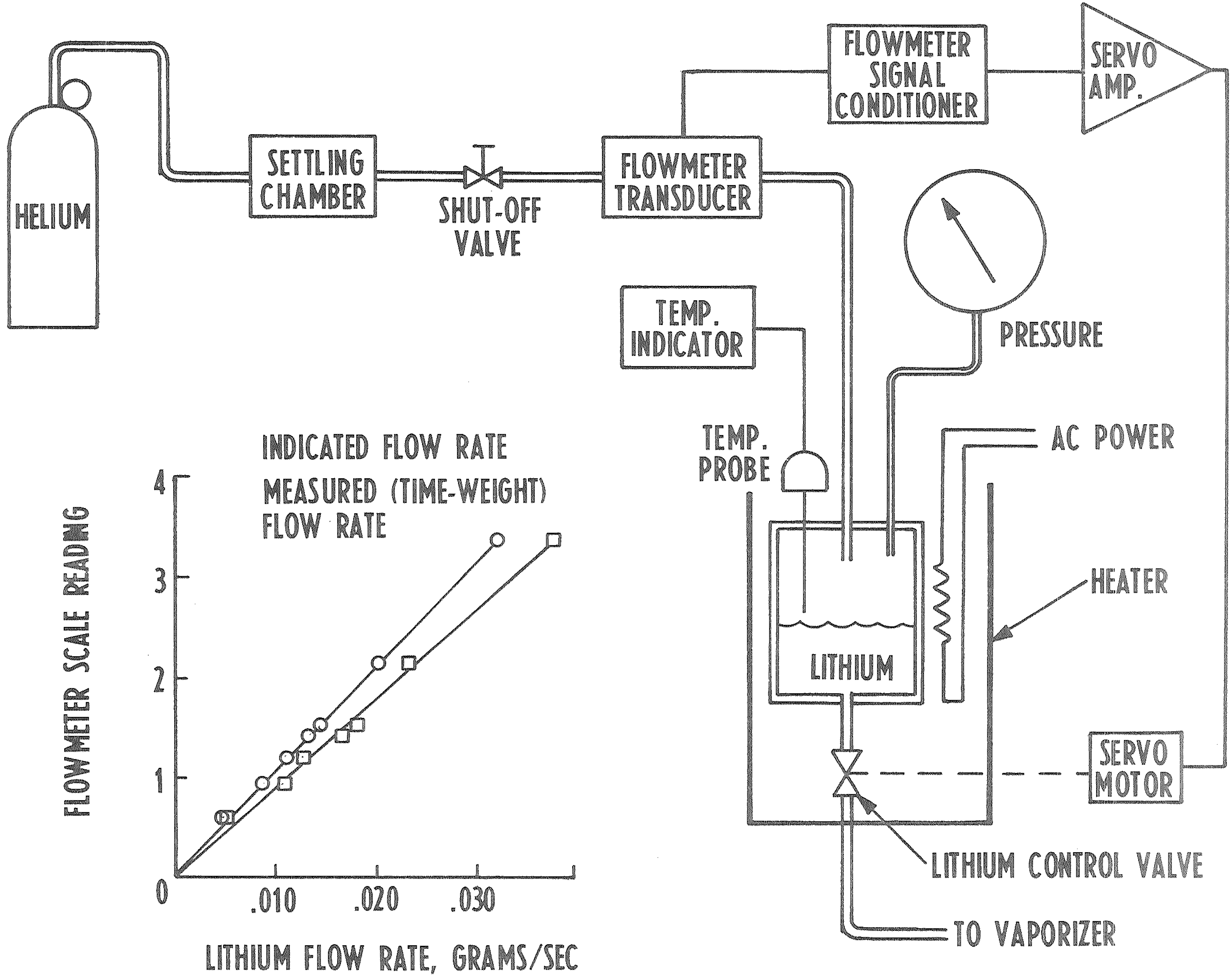

FIG. 10 MOLTEN LITHIUM FLOW SYSTEM.

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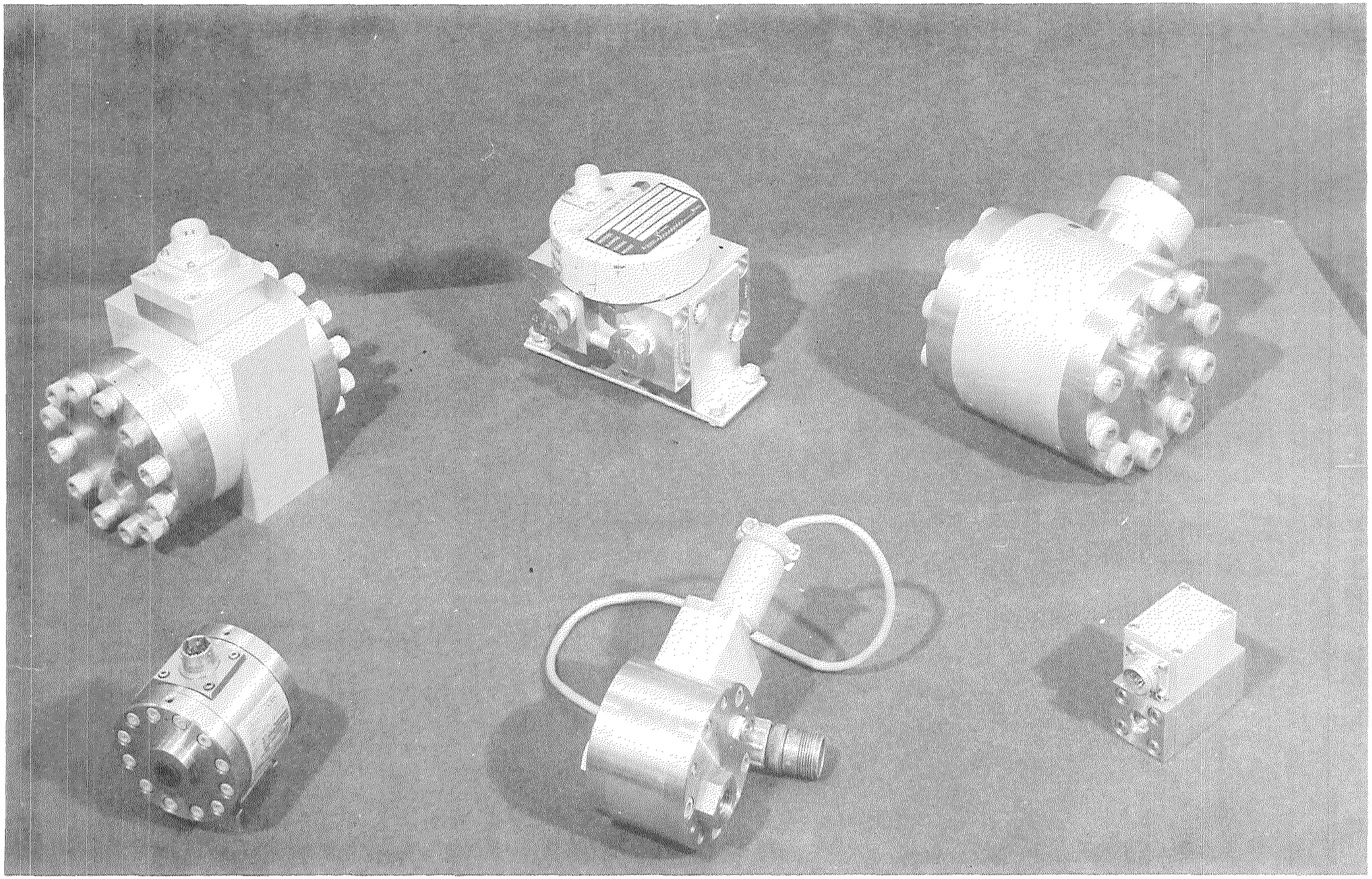

FIG. 11 DIFFERENTIAL PRESSURE TRANSDUCERS CURRENTLY USED AT LRC FOR COMPRESSED GAS FLOWS.